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Design development and performance evaluation of photovoltaic/thermal (PV/T) air base solar collector

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ABSTRACT

Recently, photovoltaic/thermal (PV/T) solar collectors are popular technologies towards harvesting solar energy. A PV/T collector is a combination of photovoltaic and solar thermal components integrated into one system that capable of producing both electrical and thermal energy simultaneously. The concept and design of a PV/T collector are being developed in order to improve the electrical efficiency of a photovoltaic module at high temperature. This paper elaborates literatures of the design developed and the performances of a PV/T air base collector. Early research works in this area until recently are focusing on their design characteristics and results. This report also covers research works on future development of a PV/T collector as a building integrated photovoltaic/thermal (BIPVT) system. It clearly shows that, by appropriate architectural design and configuration, the future of a PV/T collector can be encouraging as an alternative application in the residential, industrial and commercial buildings.

Contents

1. Introduction

Renewable energy technologies have accounted for 13.3% of the world primary energy needs Nobuyuki [71]. Exploiting local available resources, overcoming the environmental challenges, public acceptance and policy are the key challenges to increase the percentage of contribution. Over the years, various research activities had been carried out all over the world to utilise solar energy. Major reasons for such activities were the concern of global issues; global warming, the increasing price of oil and gas and the peak oil concept [1]. International Energy Agency (IEA) world oil forecast data showed that the production of crude oil and field of crude oil yet to be developed show decreasing trends towards 2030 compared to the world utilisation of oil [2]. Research has shown that air pollution from production and utilisation of fossil fuel are the primary causes of global warming [3]. Fossil fuel leads to long term environmental issues such as acid rain and green-house effect [4]. Under these conditions, the sustainable and environment-friendly energy resources such as solar energy has been identified as one of the promising source of energy to replace the non-renewable energy resources.

Technologies toward harvesting solar energy can be divided into three main applications, namely:

1. Solar thermal energy. A collector is used to capture heat from the sun. The captured heat will be used directly or stored for providing warm water, space heating and drying purposes [5].

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2. Solar photovoltaic (PV) power. Series of photovoltaic panel will be used to convert sunlight into electricity through the photovoltaic effect [5].
3. Solar photovoltaic–thermal energy. It is a combination of photovoltaic (PV) and solar thermal components integrated into one system and able to generate electricity and heat simultaneously [6].

During 1770s, the first solar thermal collector was built. The figure was cone and able to boil ammonia that would then act like refrigeration. Since then solar thermal energy was used extensively to get hot water and space heating. During 1880s the first light converting to electricity, photovoltaic cells were built. The cells were made of selenium and had an efficiency of one to two per cents. Nowadays, both solar thermal collector and photovoltaic cells are widely commercially available.

One of the crucial factors that affect the popularity of photovoltaic module is it relatively low in efficiency. Until today, commercially available photovoltaic module efficiency claimed by manufacturers is from 6% to 16%. However, the claimed efficiency is at a temperature of 25 °C. In reality, especially for countries with hot weather, their ambient temperature during a sunny day would be more than 35 °C. The rising of the PV temperature will result in the drop of module efficiency.

Nowadays, most of the commercial PV modules are made up of a thin layer of silicon semiconductor. The band gap of a semiconductor tends to decrease with the increase of temperature. When the temperature increases, the amplitude of atomic vibration increases, therefore, the space between atoms will also increase. These will reduce the size of the band gap. When the band gap gets smaller, most of electrons from the conduction band will fall back to the valence band and become with holes. These reduced numbers of moving electrons in the conduction band hence reduce the efficiency of the solar cells. Akyuz et al. [7] had developed a new approach to calculate the exergy efficiency of a photovoltaic system. Experimental data from Turkey were used to compare the new approach and the classical ways of calculation. Global solar radiation, wind speed, ambient temperature, cell temperature, voltage and current were measured in order to calculate the exergy efficiency. Mekhilef [8] had conducted studies and proved the impact of dust accumulation, humidity level and air velocity on the efficiency of a photovoltaic cell.

A basic diode model to show the relationship between the short circuit current (I_{sc}), the open circuit voltage (V_{oc}) and temperature (T) had been established [9]. Eqs. (1) and (2) show the relationship towards temperature dependent, I_o is the diode saturation current, k is the Boltzmann constant, q is the element charge, γ is a parameter used to accommodate other temperature dependencies. By calculation, it was concluded that, for typical silicon based PV, the efficiency of the cell would decrease 0.5% with 1 °C increase in temperature.

$$I_{sc} = I_o(e^{qV_{oc}/kT} - 1) \tag{1}$$

$$\frac{dV_{oc}}{dT} = -\frac{V_{g0} - V_{oc} + \gamma\left(\frac{kT}{q}\right)}{T} \tag{2}$$

In order to minimize PV module from losing its efficiency, a simultaneous cooling system using air or water as the heat transfer liquid can be implemented. The heat output from the system can be collected and stored as thermal energy. This advanced system is known as PV/T technology. For the last 40 years, there have been significant amounts of research and development work on PV/T technology [6]. PV/T solar collector system can be classified as PV/T/water system and PV/T/air system. PV/T/water systems are more efficient than the PV/T/air due to its high thermo-physical properties [10]. However PV/T/air systems are more extensively studied due to their low constructions and operational costs and cost effective solution for building integrated PV system. Therefore, this study review will be focusing on PV/T air base systems.

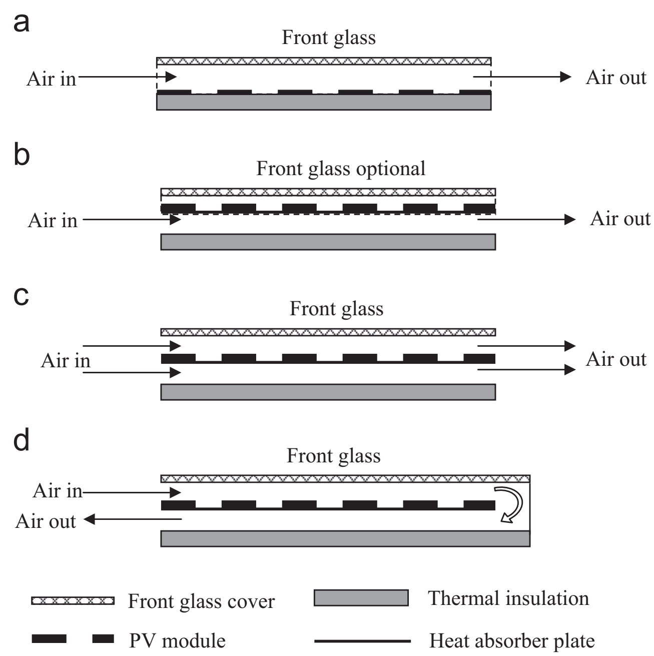


Fig. 1. Longitudinal cross-section view of common design of PV/T air base collector [6].

1.1. Common PV/T air base collector design

A PV/T solar collector is a combination of photovoltaic panel (PV) and solar thermal components or system which is capable of producing both electrical and thermal energy simultaneously in one integrated system. The photovoltaic panel could be from the selection of monocrystalline silicon, polycrystalline silicon, amorphous silicon or thin-film solar cell. The solar thermal components are various designs of a solar thermal collector which collects heat from the back of the PV panel. Fig. 1a to d show some of the common PV/T air base collector designs from the view of longitudinal cross-section [6].

The objective of this paper is to focus on the development of design and performance of an air base PV/T collectors. The latest development work, application of an air base PV/T as building integrated and future development in air base PV/T collector will be further discussed.

2. Initial developments of air based PV/T

Early research work for PV/T started in 1970s. During these decades, the research work focused more on fundamental theories, conceptual ideas and feasibility studies on basic PV/T solar collector. Wolf [11] had analysed the performance of a combination solar photovoltaic and solar heating system (PV/T) of a two storey structure, single family residence in Boston, U.S.A. The area of the design system was 50 m^2 consisted of a silicon solar array, non-concentrating thermal collector, lead-acid battery for electricity storage, heating system and water tank for thermal storage. A comparison had been made between combination system and single-purpose system. From the analysis, it was clearly indicated that a combination system is technically feasible and cost effective.

An ideal cylindrical light collector for solar concentration had been invented [12]. The ideal cylindrical light collector has a capability to receive 8 h solar radiation per day. The designed flat-plate concentrating configuration was able to collect scattered light and suitable to be used for central power and building heating or cooling. Florschuetz [13] had modified the well-known Hottel–Whillier model to analyse the performance of combined photovoltaic/thermal flat plate collectors. The modifications were based on the cell array efficiency and the decrease of cell efficiency with temperature. The extended model was applicable for plain photovoltaic collector system with forced or natural cooling method. The result of investigating performance of water and air cooled PV/T system had been presented [14]. Among the early works, Hendrie [15] had also evaluated the performance of a combined PV/T system.

During 1980s, more research work had been done and documented. Various potentially designs of PV/T collector had been investigated in order to demonstrate their best performance. Factors that influenced the efficiency of an air PV/T collectors were found to be the photovoltaic cell packing factor, solar irradiance, infrared radiation and the fluid ability to transfer the heat from the photovoltaic cell. A combination considering of flat-plate PV/T collector using computer simulation had been designed [16]. Fig. 2 shows the cross-section of the design that had been investigated.

Top air channel was a static air channel for insulation, and the bottom channel was the fluid flow channel for heat transfer. Both channels were separated by a sheet of glass attached to single crystal silicon PV cells on it. The ability of the PV cells to absorb solar spectrum were examined.

Three principle variables known as cell metallization, secondary absorber and glass emissivity were used in eight combinations in order to evaluate the electrical and thermal efficiency of the design. The work inferred that in order to achieve optimum performance of an air PV/T collector design, the back of the PV cells should be gridded, a nonselective secondary absorber should be used and finally a low emissivity heat-mirror should be used to cover the PV cells.

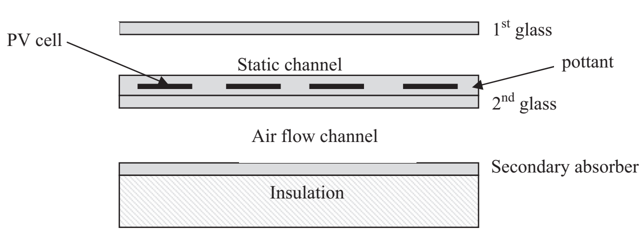


Fig. 2. Cross-section air PV/T [16].

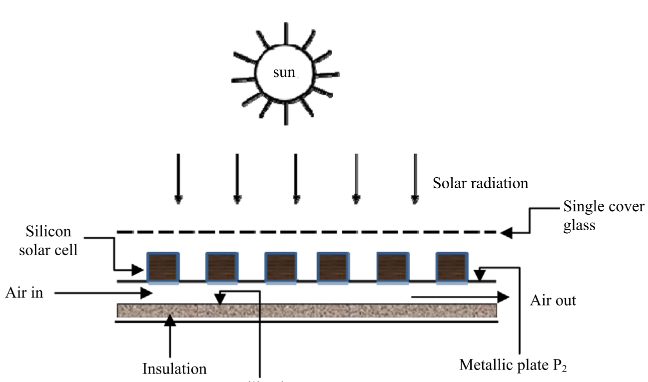


Fig. 3. PV/T system showing the two metallic plates [18].

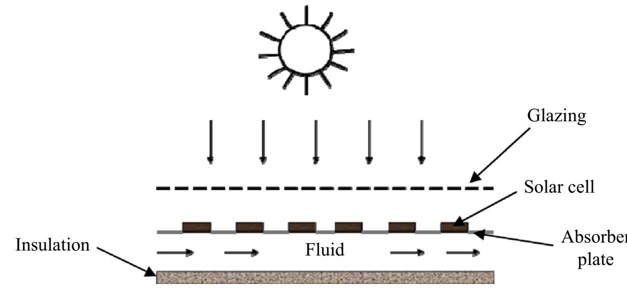


Fig. 4. Cross-section of the air PV/T system [10].

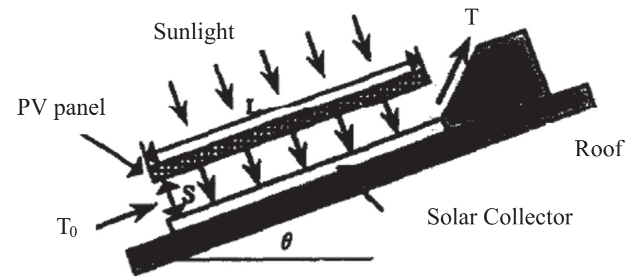


Fig. 5. A new PV/T model [22].

Starting of 1990s, research works for air base PV/T collector increase rapidly. A group of researchers [17] had studied a PV/T system consists of flat air solar air heater, solar cell and plane booster reflector. They found out that the usage of booster has increased the thermal efficiency, but decreases the electrical efficiency of the system. The designed system is suitable as solar dryer. During the same decade, Bhargava [18] had developed a hybrid system operated by solar radiation. Air acted as the heat transfer fluid flow between 2 metallic plates. Fig. 3 shows the system design.

A transient analysis for a PV/T system had been conducted in Delhi [10]. System efficiency for air/water heating at various flow rates and various fluid duct depths had been investigated. Fig. 4 shows the design of the PV/T system. Results showed that thermal efficiency for water heating system varies from 50% to 67%, and for air heating system, it varied from 17% to 51%.

Sopian et al. [19] had developed a steady state model to analyze the performance of a single pass and double PV/T solar collector system suitable for solar drying. Another simulation model on PV hybrid system had been developed by Bergene [20]. The overall efficiency of the system was predicted to be from 60% to 80%. Garg [21] had also developed a simulation model of a PV/T air base solar collector. Numerical calculations were made using typical data of climate in Delhi, India.

Another PV/T system had been evaluated in terms of its electricity and solar thermal energy efficiency [22]. A new PV/T model had been proposed that was capable to produce electricity and heat efficiently. Fig. 5 shows the proposed model.

A PV panel was placed parallel to the solar collector. There is an air gap in between them. The temperature of the PV panel would be cooled by natural convection method. The solar cells for the PV panel were packed on a transparent material so that the radiation would be able to pass through the material and reach the solar collector.

3. Early developments in the 2000s

Almost four decades now the concept of PV/T system studied, discussed and published. Both water and air are suitable to as the

cooling fluid to cool the PV module in order to avoid the drop of electrical efficiency. However, air based PV cooling system is more simple and economical due to its minimal usage of material and low operating cost. A high thermal conductivity material together with natural or forced flow of air located at the back of the PV module shall remove the heat through convection and conduction heat transfer.

Review papers on PV/T collectors written by many researchers. An interesting review work [23] covers in detailed state-of-art on a flat plate PV/T collector classification, design, performance evaluation of water, air and combination of water and air. Different feature designs and performance of each collector were compared and discussed together with future development of PV/T collectors. Another author [24] had reviewed the numerical model analysis and qualitative evaluation of thermal and electrical output of various systems. An overall thermal energy and exergy had been studied. Based on the reviews, they had concluded that in the future, the PV/T technology is a very promising system for building integration. Other than that, different author [25] had discussed a critical review of PV/T collector for air heating. An integrated PV/T for space heating and drying purposes deliver more useful energy per unit collector area when compare with standalone PV modules or thermal system.

Another review work [26] had covered in-depth performance parameters such as, optimum mass flow rate, PV/T dimensions and air channel geometry. Experimental work done by various researchers had been particularly discussed. Finally, the author had suggested ways to improve PV/T system efficiency in order to reduce their cost. This will make the system more competitive in the current market. Finally, a group of authors [27] had reviewed R&D works and practical application of the recently emerging PV/T technology. Finding from the works has enabled understanding of the current status of the PV/T technical development as well as identify the potential difficulties and barriers in this sector. As a conclusion, the authors had mentioned potential research directions for further improve the performance of the PV/T and promote its market exploitation throughout the world.

Meanwhile, performance of four models of PV/T collector had been investigated [28]. Both single pass and double pass system had been evaluated. For each model, heat balance equation were identified and solved. PV/T collector as shown in Fig. 6 gave the best performance among the others. The overall efficiency was 55% at specific mass rate of 0.04 kg/s/m^2.

Sopian et al. [29] had continued his previous work to investigate the performance of a double pass PV/T solar collector suitable for solar drying system. First, the air will flow at channel between the glass cover and the PV panel, and then it will flow through the

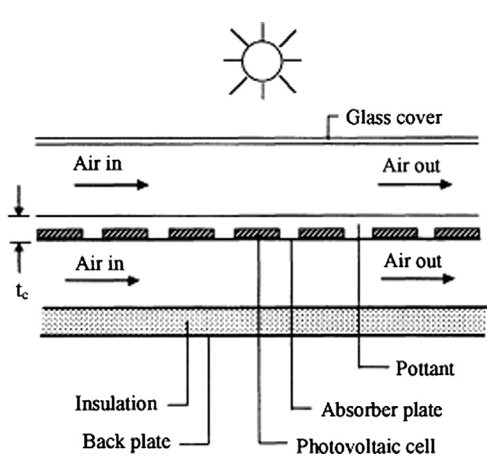


Fig. 6. Single pass PV/T with channel above and below [28].

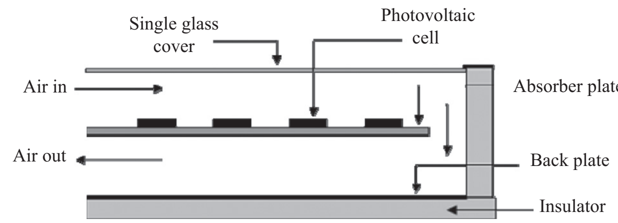


Fig. 7. Double pass PV/T system suitable for drying system [29].

second channel between the PV panel and the back plate. Fig. 7 shows the designed system. This flow arrangement increases the heat removal and reduces heat loss.

Huang et al. [30] had designed an integrated PV/T system to measure the thermal performance using the daily-efficiency test procedure. The main concept of the evaluation was primary-energy saving. Eq. (3) was used for the evaluation.

$$E_f = \frac{n_e}{n_{\text{power}}} + n_{th} \tag{3}$$

E_f is energy-primary saving, where n_e is the electric power efficiency for solar PV, n_{power} is the electric power generation efficiency for a conventional power plant, n_{th} is the heat collection efficiency of the PV/T system.

Tripanagnostopoulos et al. [31] had presented an outdoor result on hybrid photovoltaic/thermal solar systems. Both water and air was used as the heat removal fluid. Booster diffuse reflectors of aluminium sheet were introduced to the system for cost effectiveness. Systems with glazing and non-glazing were also investigated. Booster diffuse reflector was capable to increase the incoming solar radiation up to 50%. As the results, the electrical output increased by 25% to 35%.

Zondag et al. [32] had performed a study on nine different designs concept of combined PV/T water and air solar collector system. The designs concept was divided into four different groups. Fig. 8a shows the concept of show sheet-and-tube PV/T collector. Two types of PV panel were investigated; conventional opaque PV panel and transparent PV panel. Fig. 8b shows channel PV/T collector, Fig. 8c shows free flow PV/T collector and Fig. 8d shows two absorber PV/T collectors. Results conclude that 52% thermal efficiency was achieved for an uncovered PV/T collector, 58% for single cover sheet-and-tube design and 65% for typical channel above PV design. Analysis from all designs concept concludes that the single cover sheet-and-tube collector was the best design and a prototype had been developed and evaluated.

Cartmell et al. [33] had carried out a simulation study throughout a year at the Brockshill Environment Centre, Leicester, UK. Ventilated photovoltaic system (VPV) and solar air collector system (SAS) were adapted to the building as part of the building components. Projected outcome from the project was compared with Energy Consumption Guide 19 [34]. Annual energy use (kW h/m^2) in term of electricity is expected to reduce by 48%, and energy by using oil will reduce by 50%. Annual carbon emission (kg/C/m^2) was expected to reduce by 42% from electricity usage and 24% by usage of oil. Coventry [35] had designed and evaluated a PV/T solar collector namely combined heat and power solar (CHAPS) collector. It consisted of glass-on-metal mirror as the concentrator that focuses light onto monocrystalline silicon solar cell. Water was used as the fluid for heat exchanger. CHAPS achievements were compared with conventional flat plate solar collector. Under typical weather condition, the electrical efficiency of the system was around 11%, and thermal efficiency was around 58%.

Othman et al. [36] had designed, fabricated and analysed a double pass PV/T system with compound parabolic concentrator

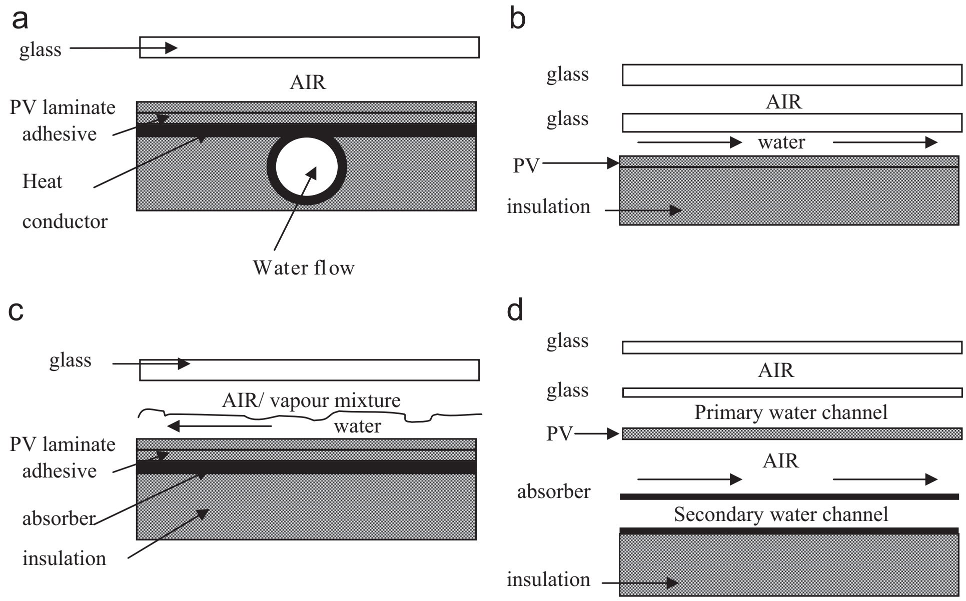


Fig. 8. Combined PV/T water and air collector [32].

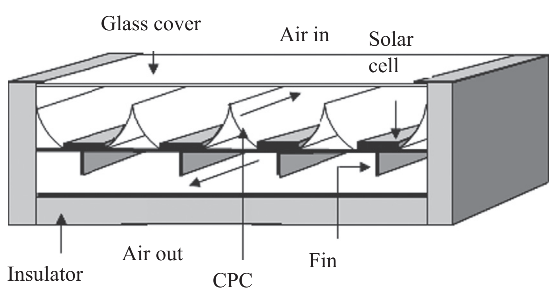


Fig. 9. PV/T with CPC and fins [36].

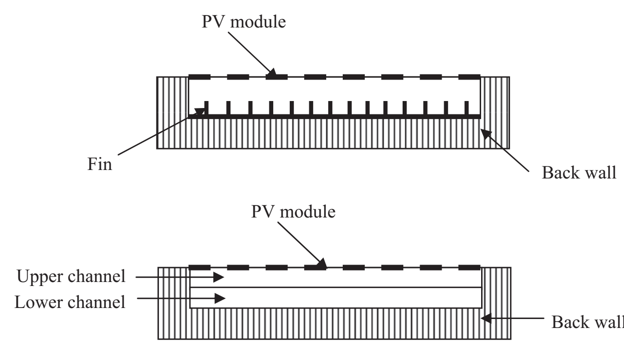


Fig. 10. Cross-section view of unglazed air PV/T with improved design [39].

(CPC) and fins. CPC with concentration ratio 1.86 was used to increase the radiation intensity fall onto the solar cells. Fins attached at the back of the PV absorber plate act as the heat exchanger. Fig. 9 shows the concept of the PV/T system. Result at radiation intensity of 500 W/m^2 shows that the combined efficiency of the system varied from 39% to 70% at mass flow rate of 0.015 kg/s to 0.16 kg/s. The experimental result agreed with the predicted result.

Karim [37] had studied the performance of a solar collector with v-groove heat absorber. The design system was suitable for drying application. The efficiency of the system with v-groove was 12% more efficient than the flat plate collector. Mattei et al. [38] had studied the influence of meteorological parameter; solar irradiance, ambient temperature and wind speed towards the performance of a PV module. Results obtained from the experiment were similar with the literature and previous works.

Tripanagnostopoulos [39] had carried out a study on two low cost improved designs of heat remover placed in a channel of a PV/T system. The improved designs involved were by introducing a thin metal sheet (TMS) at the centre of the channel and fin (FIN) attached to the back wall of the channel. Both metal sheet and fin were fabricated locally using available cheap material. In order to enhance the absorptivity and emissivity towards the solar irradiance, both designs were painted in black. Fig. 10 shows the two improved designs of the heat extraction.

Glazed PV/T system and unglazed PV/T system had also been investigated. Results showed a satisfactory agreement between prediction data from a theoretical model and measured data from experimental. Glazed PV/T system increased the thermal efficiency, but the electrical efficiency dropped. As a conclusion, the FIN PV/T system was able to give higher thermal efficiency as compared to TMS PV/T system.

Once again Tripanagnostopoulos [39] had carried out an experiment to improve the performance of a PV/T system at Universiti of Patras, Greece. A dual heat extraction operation, a combination of water and air PV/T system were investigated. Three alternative models of passing the water inside the air channel were tested. For air heat extraction improvement, the modifications were including the placing of a thin corrugated metallic sheet, located in the middle of a channel, attached small ribs on the opposite wall of PV module and placement of light weight pipes along the channel. In order to enhance effective operation on horizontal building roof, a booster diffuse reflector was combined with the PV/T system. Fig. 11a–c show the modification designs of the heat extraction.

Ebrahim [40] had developed and presented a mathematical model and solution procedure for both sides of single pass air base solar collector with CPC and fins. Gear implicit numerical scheme were used. The simulation model was very useful for predicting the performance of a PV/T system. It shows that when the system operates at high mass flow rate, the efficiency will increase.

Othman et al. [41] had carried out a performance study on a double pass air base PV/T system with fins attached at the back of the absorber plat of the PV module. Fig. 12 shows the diagram of the PV/T system. The height of the above channel was fixed, but the height of the channel below could be adjusted to observe the

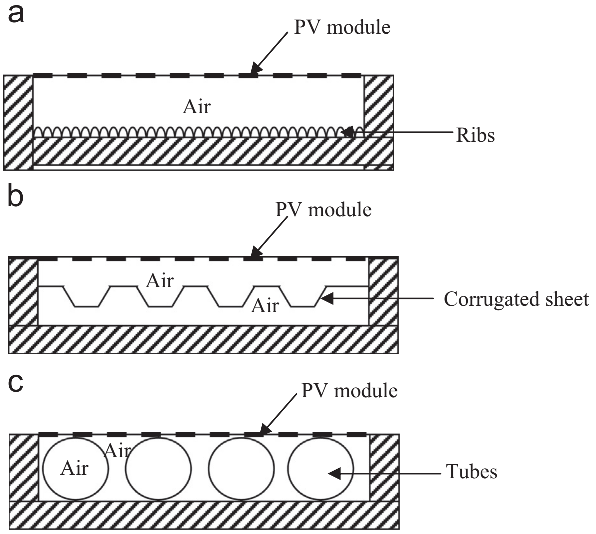


Fig. 11. Improvement of PV/T design implemented [39].

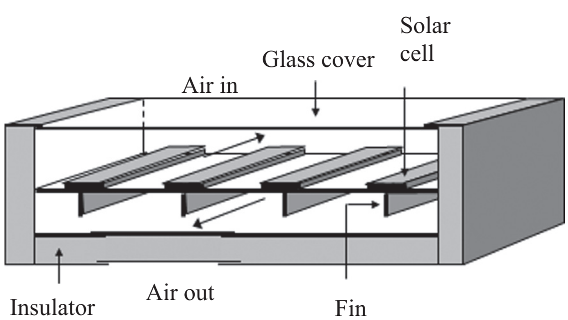


Fig. 12. PV/T with and fins [41].

performance of the system. The experiment concluded that using fins as the integral part of the PV module would be able to increase the overall efficiency of the system.

Aste [42] had presented the result on research and development of a hybrid PV/T collector done in Politechnico di Milano. The research study has led the development of innovative building component, TIS (integrated solar roof) programme. Joshi et al. [43] had evaluated the performance of two types of hybrid PV/T system, one type used glass-to-tedlar PV module and another type used glass-to-glass PV module. The experiment was carried out in New Delhi. PV/T system with glass to-glass gave better results for thermal efficiency. Overall efficiency for both systems decreases if the length of the duct increases.

Chow et al. [44] had studied the issue of glazing and unglazed of PV/T from thermodynamic viewpoint. Energy (thermal and electrical) and exergy (cell efficiency, packing factor, water mass to collector area ratio, wind velocity) analysis of the PV/T system with and without glass cover were investigated. It involved two units of identical photovoltaic–thermosyphon water heating collector system. From the scope of the experiment, it was concluded that energy efficiency (first law) is better for glazed system (50.3% vs 40.8%) and exergy efficiency (second law) is better for unglazed system (9.3% vs 12.1%).

Sopian et al. [45] had evaluated thermal efficiency of double pass PV/T system with porous media at the lower channel. Fig. 13 shows the design of the PV/T solar collector. Experimental result proved that by introducing the porous media at the lower channel has increased the heat transfer area which leads to the increase of the thermal efficiency of the system (60% to 70%). Such design system was suitable for drying application.

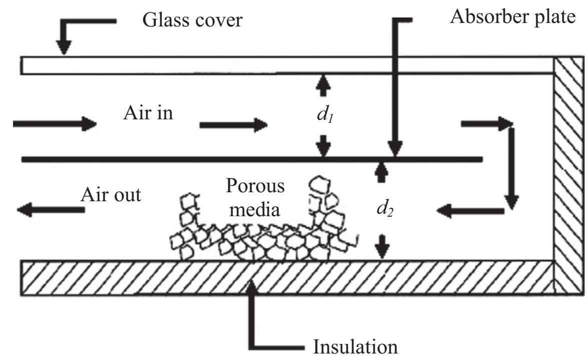


Fig. 13. Double pass PV/T system with porous media [45].

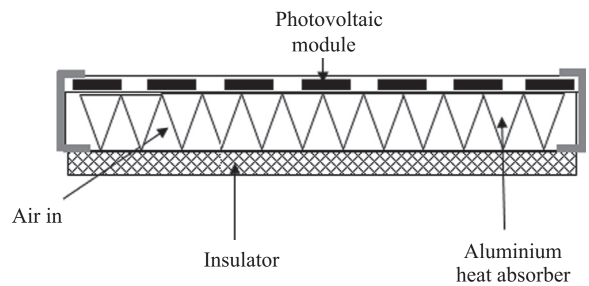


Fig. 14. PV/T system with aluminium ∇-grooved absorber plate [46].

Othman et al. [46] in his work had studied the performance of a single pass PV/T system with aluminium ∇-grooved absorber plate. The thickness of the aluminium was 0.7 mm, attached at the back of the PV module. Fig. 14 shows the cross-section diagram of the PV/T system. Results from the experiment showed that by introducing the ∇-grooved absorber plate, the electrical efficiency had been improved by 1%, and the thermal efficiency was improved by 30%.

Solanki [47] had developed an indoor testing procedure for PV/T solar heater system connected in series. The results using the indoor facilities was similar to the results tested outside. Dubey [48] had investigated methods to improve the overall annual electrical efficiency of a PV/T system in New Delhi. Four different configurations of a PV/T system were evaluated; glass to glass PV module with duct, glass to glass PV module without duct, glass to tedlar PV module with duct and finally glass to tedlar PV module without duct. Theoretical and experimental results showed that the glass to glass type PV module with duct gives the higher electrical efficiency among the others. The annual average electrical efficiency for type glass to glass PV module with duct was found to be 10.41% and for glass to glass without duct was 9.75%.

4. Recent developments of PV/T air collector

There are numerous methods of enhancing the performance of PV/T air collector. Years of research had been conducted by researchers, scientists and engineers all over the world to develop an efficient PV/T air collector. In early 2010, Shahsavar [49] had tested a direct coupled PV/T system outdoor in Kerman, Iran. The design of the system used a thin aluminium sheet placed in the middle of the air channel as the heat exchanger to cool the PV panels. The fabricated glazed and unglazed systems were tested with natural air flow and forced air flow using two, four and eight fans power. The experiment concluded that maximum electrical efficiency was achieved at an optimum number of fan used and

glazed PV panels has increased the thermal efficiency but decreased the electrical efficiency of the system.

Jin [50] had evaluated the performance of a single pass air base solar collector with rectangular tunnel heat exchanger. The material of the rectangular tunnel was aluminium. Fig. 15 shows the design of the PV/T system. Results show that the PV/T system with tunnel has better performance compared to conventional PV/T. Electrical efficiency and thermal efficiency were found to be 10.02% and 54.70%, respectively, at irradiance 817.4 W/m^2 and mass flow rate of 0.0287 kg/s.

Kumar [51] had investigated solar air heater system with double pass configuration. Vertical fins were attached to the back of the second channel to enhance heat transfer from the PV module into the airflow. The performance of the system was evaluated with and without fins. Steady state analysis of the system had been performed in detail. Results show that the system with fins had increased the thermal and electrical efficiencies to 15.5% and 10.5%, respectively, compared to the system without fins. The fins in the lower channel had successfully reduced the cell temperature and enhanced the overall performance of the PV/T system.

Teo [52] had designed a PV/T solar collector with an active cooling system to increase the electrical efficiency of a PV module. A parallel array of ducts with inlet/outlet manifolds was attached to the back of the PV module. Fig. 16 shows the design of the manifolds. Outcome from the experiment showed that the cooling system enables the electrical efficiency of the system to increase from 8–9% to 12–14%.

Hussain et al. [53] had evaluated a single pass air base photovoltaic/thermal solar collector with hexagonal honeycomb heat exchanger. A commercially available monocrystalline silicon PV module was used to produce the electrical energy. As for the thermal components, five pieces of corrugated aluminium sheet were joined together to fabricate a hexagonal honeycomb heat exchanger. The honeycomb was installed horizontally into the channel located at the back side of the PV module in order to enhance the thermal efficiency of the system. The system was tested with and without the honeycomb heat exchanger using solar simulator with irradiance of 828 W/m^2. The range of the mass flow rate during the experiment spanned from 0.02 kg/s to 0.13 kg/s. It was observed that the aluminium honeycomb heat exchanger capable of enhancing the thermal efficiency of the system efficiently. It was found that the thermal efficiency of the system is 87% at mass flow rate of 0.11 kg/s. The electrical efficiency of the PV module remains almost the same for both systems. This design is suitable to be further investigated as solar drying system.

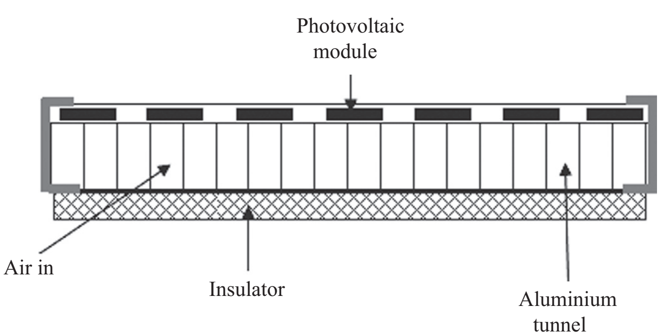


Fig. 15. PV/T system with rectangular tunnel heat exchanger [50].

Once again Hussain et al. [54] had carried out a study on three different designs of heat exchanger, v-groove, honeycomb and stainless steel wool. They were tested to evaluate their effectiveness to improve the overall performance of a PV/T air base solar collector. The material for both v-groove and honeycomb was aluminium. Heat exchangers were installed horizontally into the channel located at the back side of the PV module in order to enhance the thermal efficiency of the system. It was observed that at mass flow rate of 0.11 kg/s, the maximum thermal efficiency of the system with v-groove is 71%, stainless steel wool is 86%, and honeycomb is 87%. The electrical efficiency of the system is 7.04%, 6.88% and 7.13%, respectively.

Among the latest research work in PV/T, Bambrook [55] had conducted an investigation on the influence of fundamental parameter values in order to maximize the energy output of a PV/T air system. Experimental design involved measuring the outlet fluid temperature, heat output and mass flow rate for unglazed, single pass and open loop PV/T air system in Sydney. Karema [56] had studied in theory, the electrical and thermal performance of a single pass hybrid PV/T in Iraq. An improved mathematical thermo-electric model had been derived. Data from two cities were used to prove the model; Baghdad during winter and Fallujah during summer. The developed PV/T model was proved to be exceptionally close to other published similar research work. Recently, Pathak et al. [57] had developed a different approach for PV/T collector. Hydrogenated amorphous silicon (a-Si: H) was used as an absorber material for the PV/T system. The aim was to maintain higher operating temperatures for the thermal part.

The values added of PV/T technology as compared with other power generated technologies are noiseless, clean, proven long life span and low maintenance. Since the technology started off 40 years ago, various designs of collector had been developed and tested by many researchers. One of the challenges for this technology is to attract developers, engineers and consumers to integrate the collector into building application. However, due to many advantages of the collector, now, there are a few companies fabricate and market such collectors. The Canadian company Solar

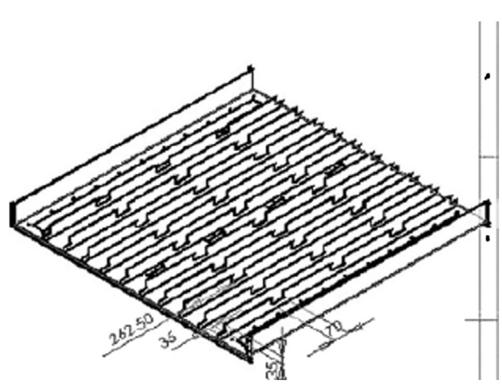


Fig. 16. PV/T solar collector with parallel array of duct [52].

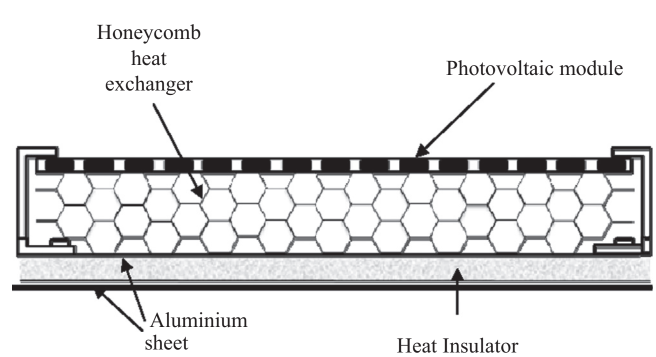


Fig. 17. PV/T system with honeycomb heat exchanger [53].

Wall [72] and Germany Solarwatt [73] are among the companies that actively commercialised the collectors Fig. 17.

5. Building integrated photovoltaic/thermal

Traditionally, for building integrated, thermal system and electrical system were constructed separately. Therefore, the installation cost is high. Nowadays, thermal system and electrical system are combined and integrated into buildings known as building integrated photovoltaic–thermal system (BIPV/T). PV/T solar collector can be installed on the roof as roof material and to wall as wall material. Therefore, the cost of building construction can be reduce as well as reduce the payback period of the building. Sandberg [58] had studied the geometrical effect of air gap behind solar cell and the location of the solar cells located on the vertical facades of a building as shown in Fig. 18. Mass flow rate (luminance flow and turbulence flow), velocity, temperature rise and location of the air gap were the parameters being verified and measured. Due to complicity to predict the amount of heat available in the air gap behind the solar cells, only buoyancy-induced flow was considered.

An interesting attempt had been made by Mei et al. [59], a dynamic thermal model for a building integrated photovoltaic–thermal, the Mataro Library, Barcelona. TRNSYS program was used for the thermal model. Heating and cooling energy required for the building was investigated with the model. Chow [60] had presented the result for applying BIPV/T concept at Southern China. A computer simulation model was developed for 260 m^2 of mono-crystalline silicon PV, installed at a hotel building of 30 storey height, and 3 different approaches had been evaluated. Results showed that there is no significant difference in electricity output between the 3 approaches.

Infield [61] had estimated the thermal performance of a ventilated photovoltaic facade applied to Mataro Spain Library. Heat loss, U and radian gain factor, g value of facade had been employed. The design of the PV facade and the air ventilation was a simple solar collector; outer PV panel at the heat absorber plate and the ventilated air as the medium for convention heat transfer. Ventilated facade had improved the performance of the PV module. Crawford et al. [62] had combined a thermal system with photovoltaic cells and integrated into building. Results showed that the concept of BIPV/T is capable to achieve energy payback periods between 4 and 16.5 years.

Chen [63] together with Canadian Mortage and House Corporation (CMHC) had designed a simulation study of a solar house with

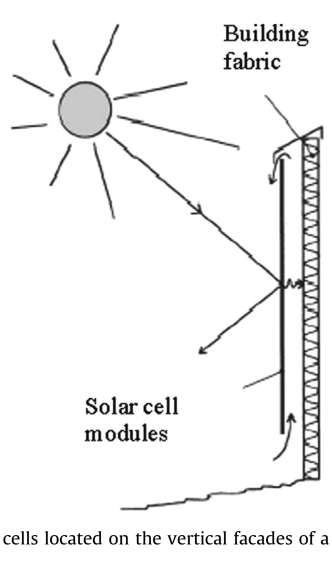


Fig. 18. Solar cells located on the vertical facades of a building [58].

BIPV/T system combined with ventilated concrete slab. The house was capable to accommodate a four-person family. 22 units of Unisolar PV panel were attached to metal roof and expected to receive 2992 W of power. Anderson et al. [66] had designed a novel BIPV/T solar collector and tested its performance. Among the key design parameters that had been investigated were the fin efficiency, thermal conductivity between the PV cells and their supporting structures as well as the usage of low cost materials. The design system was unique because it had been integrated into the building as part of the building. As a result, lower cost systems were constructed.

Agrawal [68] had installed a BIPV/T system at Srinagal, India. 48 units BIPV/T system covered 65 m^2 area of roof. Four different combinations of BIPV/T system were investigated under cold climate condition of India. Athienitis et al. [69] had studied the performance of a combination of BIPV/T and unglazed transparent collector (UTC) in building facades. The concept was applied to a full scale office building in Montreal, Canada. Recently, Bjorn [70] had analyzed a state of art review and future opportunities for building integrated photovoltaic. Various commercially available BIPV were outlined in his work. It was concluded that the future to increase commercialization BIPV with new technologies seem highly promising. New standard and method need to be developed to support the new technologies.

Recently the usage of semi-transparent photovoltaic–thermal system had been becoming quite popular. Research study carried out by Guiavarach [74] had shown that the overall efficiency for semi-transparent PV module was higher compared to opaque PV module in the case for preheating the air ventilation of a building. It was described that the number of research works in this area had been increasing. Kanchan [75] had derived an analytical expression of building integrated semi-transparent photovoltaic–thermal system for roof and facade. They had compared the result between building integrated semi-transparent photovoltaic–thermal system (BISPV/T) and building integrated opaque photovoltaic–thermal system (BIOPV/T). They had concluded that BISPV/T was more efficient and suitable for cold climate condition. Similar results also had been obtained by Wang et al. [76] and Song et al. [77].

Wong et al. [65] had anticipated semi-transparent PV modules as roofing material for building residential in Japan. A simulation model had been developed and validated. The aim of the research was to investigate the power generation, thermal and optical behaviour of semi-transparent PV module. Semi-transparent PV module with higher density had higher panels temperature; therefore the total power generation would deteriorate. A study by Fung [64] had analysed the heat transfer process through semi-transparent BIPV module using one dimensional semi-transparent photovoltaic module heat gain (SPVHG). The result of the SPVHG was compared with the experiment results. The size of the solar cells used gave significant effect to heat gain. However, PV module thickness did not affect much the heat gain of the building.

Park et al. [67] had investigated the electrical performance of a semi-transparent PV module used as glazing in building. 32 p-Si cells of 8×8 in. connected in series were encapsulated between 2 sheets of encapsulation material (Ethylene Vinyl Acetate (EAV)). Three glass sheets were used for the PV module; low iron tempered, clear, coloured and reflected types. Result showed that the temperature of PV modules influenced its electrical generation. For outdoor testing at 800 W/m^2, the power decreases 0.82% per 1 °C. The characteristic of the glasses used as the semi-transparent would influence the solar heat gain and the heat transfer on the layer.

Another important study that covers performance and life cycle cost analysis of a BIPV/T system in New Delhi [78] had proved that the installation of a BIPV/T system was more beneficial in terms of efficiency and economic point of view compared to similar BIPV

system. They had concluded that for high demand energy efficiency but limited mounting space, example for multi-story buildings, a mono-crystalline silicon BIPV/T system was the most suitable choice. Still from an economic point of view, amorphous silicon BIPV/T system was the best choice and suitable for urban and remote places.

6. Future of PV/T air collector

Currently market for solar thermal and photovoltaic system is growing continuously. Unfortunately, commercialisations for PV/T collectors are relatively low comparing to solar thermal and photovoltaic system. The potential of PV/T collectors has been identified since 1970s. Since then, PV/T collectors have received increased attention from decade to decade. The simultaneous production of heat and electricity in the same collector surface is often considered as more cost effective because less space is required, and it exhibits significantly lower balance-of-system cost [79,80].

However, the popularity and acceptance of PV/T collectors depend on many factors such as its competitiveness, technical limitations, cost-effectiveness, reliability and availability. A comparative study had been carried out by Tripanagnostopoulos et al. [81] for vertical building facade and inclined roof PV integration modes. A simple and efficient heat extraction mode suggested from this study was a roughened opposite channel surface with a thin metallic sheet (TMS) inside air channel that could serve as a low cost system improvement.

In terms of cost-effectiveness, the installation of PV/T systems generates more energy per unit area comparing to side by side installation of PV modules and solar thermal systems. High efficiency per unit area will leads to lower production cost and installation cost. For limited roof space, the installation of PV/T system able to accommodate both heat and power demand together at the same time. In the Netherland, Energy Research Centre of the Netherland [82] calculated that usage of PV/T collector possible to reduce the collector area by 40% while generating the same amount of required energy. Even though, the PV/T collectors capable of producing higher energy compare to stand alone system, the market share for such system is still negligible due to people perception that the system is bulky and not standardized. However, this limitation may change since several institutes and manufacturers are making an effort to standardize these systems [83].

In the current market, there are commercially available unglazed air types PV/T collector. However the application of air heating in the domestic market is limited. A market study had been carried out and showed that the air collectors have the market share of less than 1% of the worldwide solar collector market [84].

Presently, the price of PV module decreases slowly, this will increase the market of PV facade integrating to buildings envelope. Following this, market for PV facade with ventilation systems for heat recovery is expected to increase. PV/T systems produce better electrical yields over standalone PV module due to temperature stabilisation in the PV element of the module. Maintenance and repair cost of the air PV/T system is expected to be low and maintain throughout the years due to a complete lack of moving parts.

To boost up the PV/T collector market, the major form of incentives available today for other systems should also be applied to the PV/T system utilization such as the financial subsidies, tax reductions, low interest loan and preferential feed-in-tariffs for grid connected system. Years of technical feasibility are proven that PV/T has a broad range of application, hot water heating for domestic application (glazed PV/T collectors), ventilated PV to preheat ventilation air during winter and to provide the driving force for natural ventilation during the summer for commercial buildings.

Government's policy, architecture, construction companies and researchers are the leading group, capable to increase the market share of the PV/T application. Hence, the market for PV/T might even be larger than the market for thermal collectors.

7. Conclusion

This paper presented a review on the available literatures of design development and performance of PV/T air base technology as well as their application as building integrated. The technology has enormous potential to be further utilized. Further work on improving efficiency, cost reduction and building integrated application of PV/T air base technology seem to be vitally necessary in order to obtain optimal performance of the collector. Awareness on energy saving programme, critical issue of a clean environment and government policy will be able to enhance the development of PV/T technology. Since a few years ago, in conjunction with BIPV/T approach, PV/T air collector technology is very popular for food industries especially in tropical countries. Recently, engineers and contractors have given their attention to integrate photovoltaic panels for roof and facade of buildings. As a conclusion, by proper architectural design and configuration, electrical and thermal efficiencies can be further improved and will be beneficial to consumers. This effort will contribute to the world target which is to enhance the usage of renewable energy in residential, industrial and commercial buildings.

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